Spatial distribution of soil nutrients in a created riparian wetland

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Abstract

Spatial distribution of soil nutrients, minerals and pH, along with physical soil characteristics, were evaluated in a created riparian wetland or oxbow, called the Billabong, located in the Olentangy River Wetland Research Park at Columbus, Ohio in October 2005. Results of the soil color analysis along with presence of mottles in some locations indicate that hydric soils have developed over a large portion of the Billabong since its construction in 1996. Organic matter averaged 4.8 percent; bulk density averaged 1.3 g/cm^3; and pH averaged 7.1, which are indicative of mineral soils. Results of the 3-Mehlick Separation Technique and ICP mineral analysis averaged: aluminum 655 µg-Al/g, boron 1.6 µg-B/g, calcium 3042 µg-Ca/g, copper 4.8 µg-Cu/g, iron 492 µg-Fe/g, magnesium 483 µg-Mg/g, manganese 193 µg-Mn/g, nitrate-nitrogen 4.1 µg-NO_3/g, phosphorus 13.2 µg-P/g, potassium 92 µg-K/g, sodium 166 µg-Na/g, sulfur 143 µg-S/g, and zinc 3.7 µg-Zn/g. The highest concentrations of soil nitrate, iron, and sodium were detected at the Billabong inflow, while the highest concentrations of soil potassium, magnesium and boron were detected in an emergent *Typha* zone. Spatial distribution of soil phosphorus was consistent with the expectation that higher concentrations (18.6-21.9 µg-P/g) would be found in (captured by) the dense emergent *Typha* zone at the north end of the Billabong near the inflow and that lower concentrations (3.2-6.4 µg-P/g) would be found in the deep open water zone in the south part of the Billabong. No other parameters except zinc exhibited this spatial distribution. Where the Billabong begins to widen and surface water flow during hydrologic pulse events presumably slows, are high-highest concentrations of soil calcium, iron, manganese, sulfur and magnesium, whereas aluminum is lowest. Results of soil phosphorus, potassium, calcium and magnesium were comparable to the ORWRP preconstruction values.

Introduction

In 1996 a 2.8 hectare (7-acre) riparian wetland, called a Billabong after the Australian name for an oxbow, was created at the Olentangy River Wetland Research Park (ORWRP) at the Ohio State University in Columbus, Ohio; the Billabong was planted in 1997. This wetland was established in order to mitigate loss of 1.1 hectare wetlands at a Fairfield County, Ohio landfill (Kettlewell et al., 2002). Previous investigations of the Billabong site include evaluation of vegetation establishment in 1997, 1998 and 2000-2002 (Mitsch et al., 1998; Bouchard et al., 1999; and Anderson et al., 2003); evaluation of soil characteristics in 1998, 2000 and 2002 (Gilbert et al., 1999; Broennum et al., 2001; and Kettlewell et al., 2003); evaluation of denitrification (Filippi et al., 1998); evaluation of hydrology in 1996 and 2001 (Koreny and Bair, 1997; and evaluation of water quality and hydrology in 1997-2002, 2003 and 2005 (Anderson and Mitsch, 2003; Fink and Mitsch, 2004; 2005). This study further expands knowledge of the Billabong by conducting a spatial evaluation of soil nutrients and minerals, soil pH and soil color, percent organic matter and bulk density, with sampling locations based upon site vegetation, hydrology and morphology as described in previous investigations and as observed during the October 2005 field work.

Presence of hydric soil is one of several characteristics used to identify wetlands and is therefore important to determine the success of mitigation wetlands, including the Billabong. Wetland soils are inundated with water a sufficient period of time that anaerobic conditions develop in the upper part as necessary to support facultative and obligate hydrophytic vegetation. Anaerobic conditions and hydric soils are identified by soil color, gleying, mottling and oxidation of root zones. (Mitsch and Gosselink, 2000). Hydric soils are within the soil classification order Histosols and in Aquic subgroups (Brady and Weil, 1999).

Advantages of riparian wetlands such as the Billabong include improvement of water quality and flood storage during river flood events (Fink, draft 2005 and Pierzynski et al., 1994). Nutrients in wetland soils are important because they determine in part the success of vegetative species and because they provide evidence of nutrient capture and retention capabilities of wetlands, one of the most important wetland functions (Mitsch et al., 1995). It is through the soil that plants uptake nutrients (and certain concentrations of nutrients and minerals may be toxic to plant development although wetland plant species are more tolerant of such toxic conditions (Mitsch and Gosselink, 2000). As plants die, nutrients are recycled back into the soils continuing a cyclical pattern. In riparian type wetlands, surface water sediments are trapped by the wetland plant material which in turn helps to reduce concentrations of nutrients in outflow water.

Anderson et al. (2002) initially hypothesized that nutrient supply from the inflow (pumped river water) at the ORWRP

Wetlands 1 and 2 (situated adjacent the Billabong) may have been "disproportionately available to vegetation closer to the inflow source" and that this might lead to a greater accumulation of organic matter and hence lead to correlation between soil bulk density and percent organic matter with distance from the inflow. However, as their investigation found no such correlation, they suggested that regular movement of water through Wetland 1 and 2 "moderates the centralization of nutrients and consequently soil organic matter accumulation near the inflow". Anderson et al. (2003) further suggested however, that their hypothesis may hold true for the Billabong which generally receives a "pulsing hydrology and nutrient inputs".

Consequently, in the Billabong, higher soil nutrient concentrations were anticipated near the inflow and in high productivity vegetative zones. It is also possible that higher plant productivity may be observed near the wetland inflow than the open water areas, not only because of site morphology and hydrology, but also because of nutrient availability. It was hypothesized that the soil nutrient concentrations would be greatest in the obligate (*Typha*) vegetative zones nearest the nutrient rich inflow (and presumably greater sedimentation rates) in the northern part of the Billabong, that nutrient concentrations would decline in soils with distance from the inflow and would be least in the open water zones in the southern part of the Billabong where leaching is expected to be most prevalent. Higher nutrient concentrations were also expected in the smaller obligate vegetative zone near the outflow in the southern end of the Billabong.

Site Description

The Billabong is adjacent to and on the east side of ORWRP kidney shaped experimental Wetlands 1 and 2. The ORWRP was formerly abandoned farmland and is underlain by 33 to 83 m of glacial outwash (Mitsch, 1993; Gilbert et al., 1999). The soil types were determined to be of the Ross and Eldean series which consist of silt loam, silt clay and clay loams (Mitsch, 1993; Nairn et al., 1994; USDA, 1980).

The site is within the Olentangy River floodplain and is passively fed by river water during periods of high water levels through an inflow pipe equipped with check valve at the north end of the site and discharges by gravity through a weir at the south end of the site. As reported by Fink (2005), "the Billabong floods naturally by river pulses since it was constructed in 1996. The Olentangy River itself typically has frequent short (1 to 5 day) flood pulses, particularly December through May, producing pulses into the created oxbow." Seasonally, ground water discharges to the Billabong as well (hence it is a discharge wetland). In fact, the Billabong is about 60 cm deeper in the ground than either experimental Wetland 1 or 2 (Filippi et al., 1998).

In 2005, the Billabong was maintained with steady-flow hydrology as part of an ecosystem-scale pulsing experiment. During January 2005, the site was flooded and then stayed

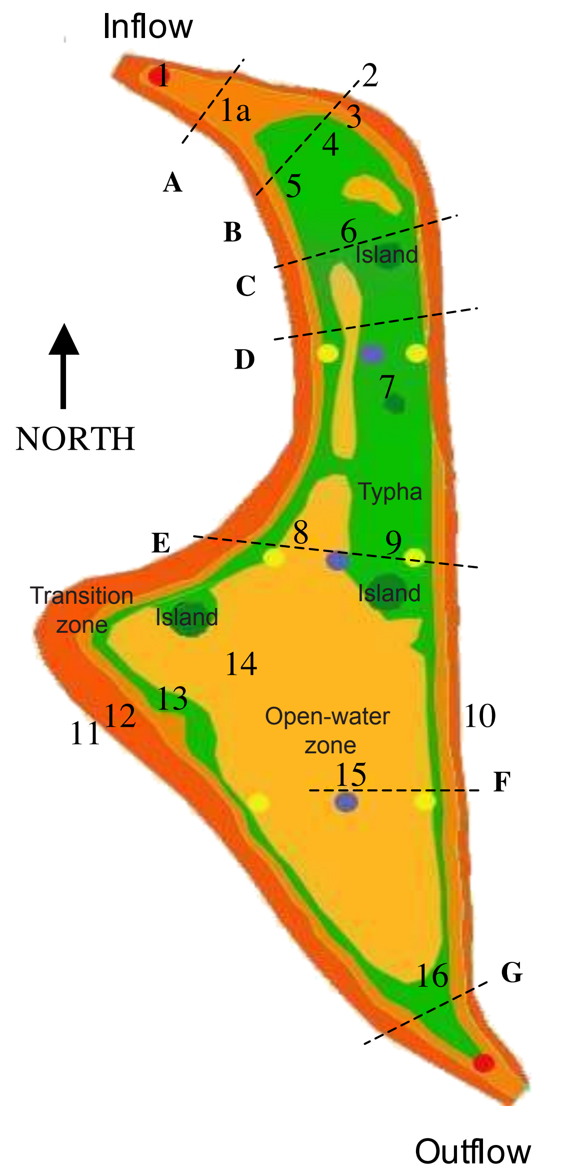

Figure 1. Billabong soil sampling locations and vegetative zones. Numbers indicate soil sampling locations and dotted lines indicate vegetation sampling transects used in other studies.

at normal river levels through the summer and fall (Mitsch, personal communication). As a result, the entire Billabong was inundated with water (gauge height = 43.3 cm) and no mud flats were observed during the October 10, 2005 field work (also, there was no surface discharge through the weir).

The slope of the edge of the Billabong is relatively steep on the east side and is gentle on the west, particularly the southwest side; the Billabong is deepest in the southcentral portion. When flooded, the primary surface water flow path appears to be through the western side of the northern half and through the center of the southern half. Normally, during the summer and fall, the Billabong has little standing water and the south end is mud flats except for a small area of open water in the deepest portion.

The Billabong vegetation is comprised predominantly

Table 1. General characteristics for each sample site.

Site Numberr	Nearest Transect	General Location	Location Description	Vegetation Type	Water Depth* (cm)
1		north	open water	submerged	30
1A	A	north	emergent	Typha	13
2	B	north	upland	grasses	-----
3	B	north	edge	grasses	-----
4	B	north	emergent	Typha	11
5	B	north	edge	grasses	-----
6	C	north	emergent	Typha	14
7	D	north	emergent	Typha	15
8	E	north	open water	submerged	22
9	E	north	emergent	Typha	17
10		southeast	upland	grass	-----
11		southwest	upland	grasses	-----
12		southwest	edge	grasses	-----
13		southwest	emergent	Typha	11
14		southwest	open water	submerged	15
15	F	south	open water	submerged	38
16	G	south	emergent	Typha	10

of *Typha* emergent marsh (obligate vegetation) in the northern third of the wetland and is mostly open water in the southern two-thirds. Around the edge of the Billabong is a transitional swath of facultative vegetation; a thin swath of obligate vegetation also surrounds most of the open water sections. A large patch of emergent *Typha* is also present at the very south end near the outflow.

Methods

Field sample locations

Soil sampling for this study was conducted on October 10, 2005. A total of 17 sites were sampled at or along transects previously established by Kettlewell et al. (2002) (six sites), at three of the sites previously sampled by Gilbert et al. (1999) and Broennum et al. (2001) and at eight new sites along a roughly north-south transect extending from the inflow to near the outflow in the deeper part of the Billabong (Table 1). Some of the new sites were also situated along east-west transects (presumably vegetation transects) observed in the field. Specifically, three upland sites were sampled on the north, southeast and southwest side of the Billabong (Sample Nos. 2, 10 and 11, respectively). Three transitional edge sites containing facultative vegetation and having no standing water were sampled on the north, northwest and southwest side of the Billabong (Sample Nos. 3, 5 and 12, respectively). Sites covered with at least 10 cm water, starting at the north/inlet end of the Billabong and moving south toward the outflow included: one sample at the inlet (No. 1); six samples (Nos. 1A, 4, 6, 7, 9 and 13) in an emergent *Typha* zone; three samples (Nos. 8, 14 and 15) in open water areas; and an additional sample (No. 16) in an emergent *Typha* zone at the south end of the Billabong near the outflow. (Figures 1 and 2).

Field methods

Soil samples were taken using a 2 cm diameter stainless steel handheld soil probe. Two cores were taken at all 17 sites and a third core was taken at 12 of the sites. The first core was evaluated in the field for soil color (hue, value and chroma) using a Munsell Soil Color Chart and checked for any gleying, mottling or oxidation of root zones of both the A and B soil horizons. Where mottling was observed the sample was "smeared" so that an average chroma and value

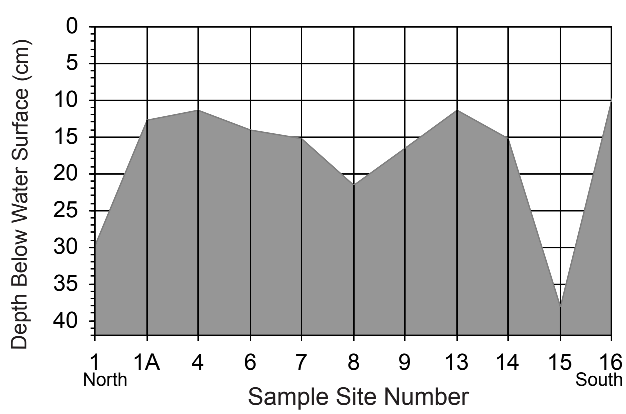

Figure 2. Bathymetric profile of the Billabong, measured on October 10, 2005, shown as the depth below water surface to the sediment at each sample location.

could be determined. The entire second core (lengths of which ranged from 21.6 to 40.6 cm) was used for laboratory analysis of soil bulk density and organic content. The top 15 cm of the third core was used for nutrient analysis and retesting of organic content. The samples were placed in plastic bags, sealed and refrigerated until sample preparation and analysis was performed.

Sample preparation and analysis

The samples that were to be analyzed for nutrients and minerals were placed in aluminum tins; as necessary, the sample bags were washed out into the tins with distilled deionized water. The samples were oven dried at 60oC for over 48 hours. Then the samples were ground by hand and re-ground in an electric grinder with vacuuming of the equipment between each sample. The thoroughly mixed samples were placed in paper envelopes and shipped to Star Laboratory at the Ohio Agricultural Research and Development Center in Wooster, Ohio for analysis of pH and LTI using the 3-Mehlick Separation Technique and ICP mineral analysis (for P, K, Ca, Mg, S, Al, Cu, Fe, Mn and Zn) and for analysis of nitrate-nitrogen.

Procedures used to analyze the samples for bulk density were taken from Kassem and Nannipieri (1995) and Kettlewell et al. (2002). The samples were dried in an oven at 105oC for over 24 hours, placed in a dessicator to cool for about 6 hours and weighed on a Metter AE 200 balance. Bulk density (grams/cm3) was computed by: (dry weight / wet sample volume). Sample volume was determined by: (cross-sectional area of the 2-cm diameter probe x sample length).

To prepare the samples for analysis of percent organic matter, the 105°C dried samples were ground by hand and then reground using an electrical grinder, with vacuuming of the equipment between each sample. Crucibles were weighed on a Metter AE 200 balance. Then approximately 6 to 12 grams of ground soil from each sample was placed in each crucible. Because of concern that the samples may have absorbed air moisture during the grinding period, the crucibles with soil samples were placed in a dessicator for 12 hours. Then, the crucibles with samples were weighed and placed in a dry muffle furnace at 550°C for three hours (one hour to heat up the furnace and two hours to combust the organic matter). Next, the oven was turned down to 110°C for two hours so that the sample containers could be handled; then the crucibles with samples were placed in a dessicator to cool; and finally, the room temperature crucibles with soil were reweighed. Percent organic matter was computed by: [(soil weight dried at 105oC– soil weight after 550°C) / (soil weight dried at 105°C)]. Procedures used were provided by Amanda Nahlik, graduate assistant, and were based on methods used in previous soil research at the ORWRC, including Kettlewell et al. (2002). Percent organic matter was re-determined for some of the samples using the soil left over from the nutrient analysis, which was from the upper 15 cm of the soil core.

Results/Discussion

Soil color

Two soil horizons were observed at all but five sites (the three upland sites [Nos. 2, 10 and 11], one emergent *Typha* site where only 21.6 cm soil recovery was achieved [No. 1A], and one edge site [No. 12]). The upper A soil horizon sampled ranged in length from 6.4 to 35.6 cm. Hue observed in all the samples and soil horizons was 10YR. The A horizon ranged in value/chroma from 2/1 to 3/4. The B horizon ranged in value/chroma from 3/3 to 5/4. A total of ten sites had a chroma of less than or equal to 3 and a value of less than or equal to 2. This included all of the sites that were under water (with depths ranging from 10 to 30 cm), with the exception of Site 15 (under 38 cm water) and Site 9 (a *Typha* zone under 16.5 cm of water). Surprisingly, Site 2, the north upland site, also had a chroma/value of 3/2. Heavy mottling was observed in the B horizon at four sites (Nos. 6, 8, 14 and 16) and in the A horizon at two sites (Nos. 15 and 16); slight mottling was observed in the B horizon at Site 9. All the mottled samples were gray with orange mottling, except near the outflow at Site 16 the A horizon was black with brown mottling and the B horizon was gray with brown mottling. (Table 2).

Wetland type hydric soils are defined as having a value less than or equal to 3 and chroma less than or equal to 2 (Mitsch, 2000). Results of the 2005 soil color analysis indicate that hydric soils have developed over a large portion of the Billabong. These results are generally consistent with previous investigations (Table 3).

Bulk density and percent organic matter

Bulk density ranged from 0.78 to 1.69 gm/cm^3 with upland site samples ranging from 1.08 to 1.25 gm/cm^3, transitional edge zone samples from 1.21 to 1.40 gm/cm^3, emergent *Typha* zone samples from 0.78 to 1.67 gm/cm^3 and deep open water samples from 1.0 to 1.69 gm/cm^3 (Table 2).

Organic matter percentages for the full core ranged from 3.4 to 7.8%. The upland samples ranged from 5.1 to 6.2%, transitional edge zone samples from 3.7 to 4.5%, emergent *Typha* zone samples from 3.9 to 7.8%, and deep open water samples from 3.4 to 4.5%. Results of re-analysis of organic matter from the upper 15 cm of soil ranged from 2.6 to 6% with samples from the emergent *Typha* zone at 3.9-6% and samples from the open water zone at 2.6-5.4%. (Table 2). Results of bulk density and percent organic matter are comparable to the 1998, 2000 and 2002 data (Gilbert et al., 1999, Broennum et al., 2001 and Kettlewell et al., 2003) (Table 4) and are indicative of mineral soils (Mitsch and Gosselink, 2000).

Soil nutrients

Soil samples at the twelve water covered sites in the Billabong (from north to south: Site Nos. 1, 1A, 4, 5, 6, 7, 8, 9, 13, 14, 15 and 16) were analyzed for pH, nutrients and minerals. A macronutrient is an element that plants

Table 2. Billabong soils field data for color analysis, bulk density and percent organic matter (measured for the entire soil sample and the top 15-cm of the sample).

Site	Water Depth	Hue Value/Chroma		Total Length	A horizon Length	Bulk Density*	Organic Matter*	Organic Matter**
	(cm)	A horizon	B horizon	(cm)	(cm)	(g/cm³)	(percent)	(percent)
1	30	10YR 2/1	10YR 5/4	34.3	16.5	1.37	4.4	3.4
1A	13	10YR 3/2	NA	21.6	21.6	0.78	5.2	4.7
2	-----	10YR 3/2	10YR 3/2	33.7	33.7	1.25	5.1	
3	-----	10YR 3/3	10YR 4/4	40.6	7.6	1.21	3.7	
4	11	10YR 3/2	10YR 4/3	35.6	10.2	1.48	4.2	4.7
5	-----	NA	10YR 4/3	33.0	8.9	1.40	4.5	4.7
6	14	10YR 2/1	10YR 4/3	33.0	6.4	1.45	3.9	6.0
7	15	10YR 3/1	10YR 3/4	35.6	NA	1.48	4.2	3.9
8	22	10YR 2/1	10YR 4/4	40.6	27.9	1.00	3.4	2.6
9	17	10YR 3/4	10YR 4/4	40.6	NA	1.67	4.6	
10	-----	10YR 3/3	10YR 3/3	31.8	31.8	1.21	6.1	
11	-----	10YR 4/3	10YR 4/3	35.6	35.6	1.08	6.1	
12	-----	10YR 3/3	10YR 3/3	35.6	35.6	1.32	3.9	
13	11	10YR 3/2	10YR 4/3	39.4	na	1.25	7.8	6.0
14	15	10YR 3/2	10YR 4/4	40.6	20.3	1.69	4.5	4.8
15	38	10YR 3/3	10YR 4/3	40.6	15.2	1.58	4.0	5.4
16	10	10YR 3/1	10YR 3/3	36.8	NA	1.46	5.3	

* utilized total sample length in analysis
** utilized 15 cm sample length in analysis

Table 3. Comparison of Billabong soil color measured at different sampling locations in 1998, 2000, 2002 and 2005.

Sample year 1998 Gilbert etal (1999)		Sample year 2000 Broennum (2001)		Sample year 2002 Kettlewell (2003)		Sample year 2005 Current Study (2006)		
Sample Site	Hue Value/ Chroma	Sample Site	Hue Value/ Chroma	Sample Site	Hue Value/ Chroma	Sample Site	Hue Value/Chroma A Horizon	B Horizon
-----	-----	Inflow	2.5YR 3/2*	-----	-----	1	10YR 2/1	10YR 5/4
-----	-----	North	10YR 3/2-3/3	North	10YR 4/4	2	10YR 3/2	10YR 3/2
-----	-----	-----	-----	North	10YR 3/2	3	10YR 3/3	10YR 4/4
-----	-----	-----	-----	North	2.5YR 3/2	4	10YR 3/2	10YR 4/3
-----	-----	South	10YR 3/2-3/3	South	10YR 4/2	10	10YR 3/3	10YR 3/3
-----	-----	-----	-----	South	2.5YR 3/2	12	10YR 3/3	10YR 3/3
-----	-----	West	2.5YR 3/	South	10YR 3/2	13	10YR 3/2	10YR 4/3
Bc	10YR 4/4	East	10YR 3/6-4/4	-----	-----	15	10YR 3/3	10YR 4/3
Bu	10YR 3/3	-----	-----	-----	-----	-----	-----	-----
Bt	10YR 4/2	-----	-----	-----	-----	-----	-----	-----
-----	-----	Outflow	2.5YR 3/2	-----	-----	-----	-----	-----

NOTE: Each study used different names for many of the same sampling locations as indicated under “sample site”.

*Report also gives Hue Value/Chroma of 10YR 4/4 for the same location.

Table 4. Comparison of Billabong bulk density and organic matter percent at different sampling locations for 1998, 2000, 2002 and 2005.

Sample Year 1998 Gilbert et al (1999)[#]			Sample year 2000 Broennum et al (2001)			Sample Year 2002 Kettlewell et al (2003)[@]			Sample Year 2005 Current Study**		
Sample Site	BD* (g/cm³)	OM (%)	Sample Site	BD (g/cm³)	OM (%)	Sample site	BD (g/cm³)	OM (%)	Sample Site	BD (g/cm³)	OM (%)
------	-------	-------	Inflow	0.72-1.15	3.9-4.7	------	-------	-------	1	1.37	4.4
------	-------	-------	North	1.06-1.39	2.5-3.9	North	1.22	4.2	2	1.25	5.1
------	-------	-------	------	-------	-------	North	0.7	6.5	3	1.21	3.7
------	-------	-------	------	-------	-------	North	0.31	15.2	4	1.48	4.2
------	-------	-------	South	1.15-1.35	3.8-3.9	South	1.45	4.3	10	1.21	6.1
------	-------	-------	------	-------	-------	South	1.25	5.2	12	1.32	3.9
------	-------	-------	West	1.12-1.38	4.8-5.4	South	0.91	4.8	13	1.25	7.8
Bc	1.4	3.3	East	1.32-1.46	3.1-3.97	------	-------	-------	15	1.58	4.0
Bt	1.2	3.8	------	-------	-------	------	-------	-------	------	-------	-------
------	-------	-------	Outflow	1.15-1.5	3.2-4.8	------	-------	-------	------	-------	-------

NOTE: Each study used different names for many of the same sampling locations as indicated under "sample site".
* estimated from graph
** used core sample length of 33.7 to 40.6 cm
[#] used core sample length of 20 cm
[@] used core sample length of 16 cm

must have in relatively large amounts to complete their life cycles: besides carbon, hydrogen and oxygen, the primary nutrients are nitrogen, phosphorus and potassium and the secondary nutrients are calcium, magnesium and sulfur. A micronutrient or trace element is an element that plants must have, but only in small amounts: boron, copper, iron, manganese, molybdenum and zinc (and nickel, cobalt and chlorine, not considered here). (Brady and Weil, 1999; Troeh and Thompson, 2005). Other minerals tested for include aluminum and sodium. Results are summarized and discussed below and, where data is available, are compared with available soil nutrient concentrations detected at the ORWRC experimental wetlands prior to and following construction.

pH - The pH of the Billabong soils is neutral to alkaline (6.6 to 7.5 pH) which is indicative of mineral soils. (Figure 3). Flooding of previously drained soils may cause alkaline soils to decrease in pH due to build up of CO_2 and carbonic acid and may cause more acid or neutral soils to increase in pH due to reduction of ferric iron hydroxides (Mitsch and Gosselink, 2000). The optimum pH for plant growth is usually between 6 and 7.5 (Troeh and Thompson, 2005).

Nitrate-Nitrogen - Nitrate-nitrogen (NO_3) concentrations in the Billabong soils are very low, ranging from 3.3 to 6.3 μg-NO_3/g and averaging 4.1 μg-NO_3/g. Site No. 1 (at the inflow) had the highest concentration; the remaining sites

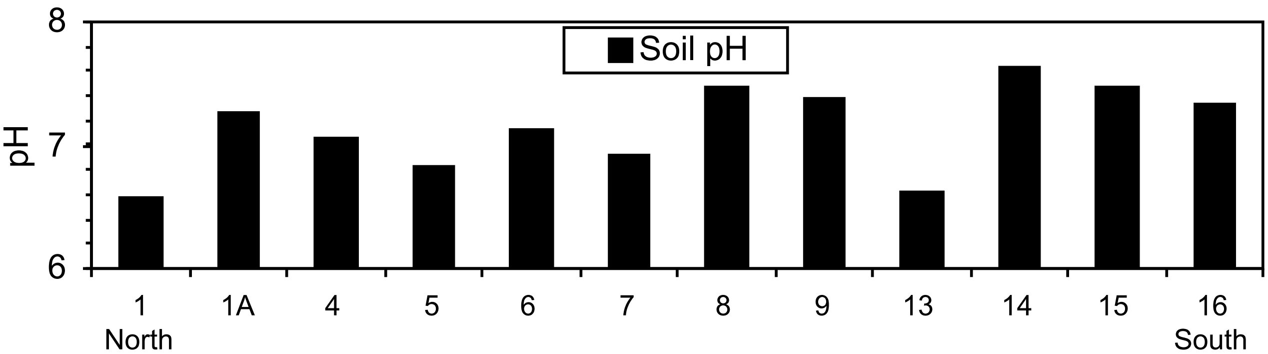

Figure 3. Soil pH for each sample location from north to south

were equal to or less than 4.6 μg-NO3/g. (Figure 4). Results of water quality analyses by Fink (draft, 2005) indicate that 92% of nitrate loss occurs in the emergent marsh portion of the Billabong wetland. Similarly, nitrate concentrations in water in the ORWRC experimental Wetlands 1 and 2 are substantially higher in the inflow water than in the outflow water (Mitsch et al., 1999).

Nitrogen is the major nutrient in fertilizers as plants need large quantities of nitrogen and little is supplied in natural soils (Troeh and Thompson, 2005). Nitrate, as discussed by Mitsch and Gosselink (2000), is relatively mobile in solution and if not assimilated immediately by plants or lost to groundwater flow, has the potential to undergo reduction to ammonia and denitrification. Denitrification is carried out by microorganisms under anaerobic conditions (as occur in hydric soils) and results in loss of nitrogen as it is converted

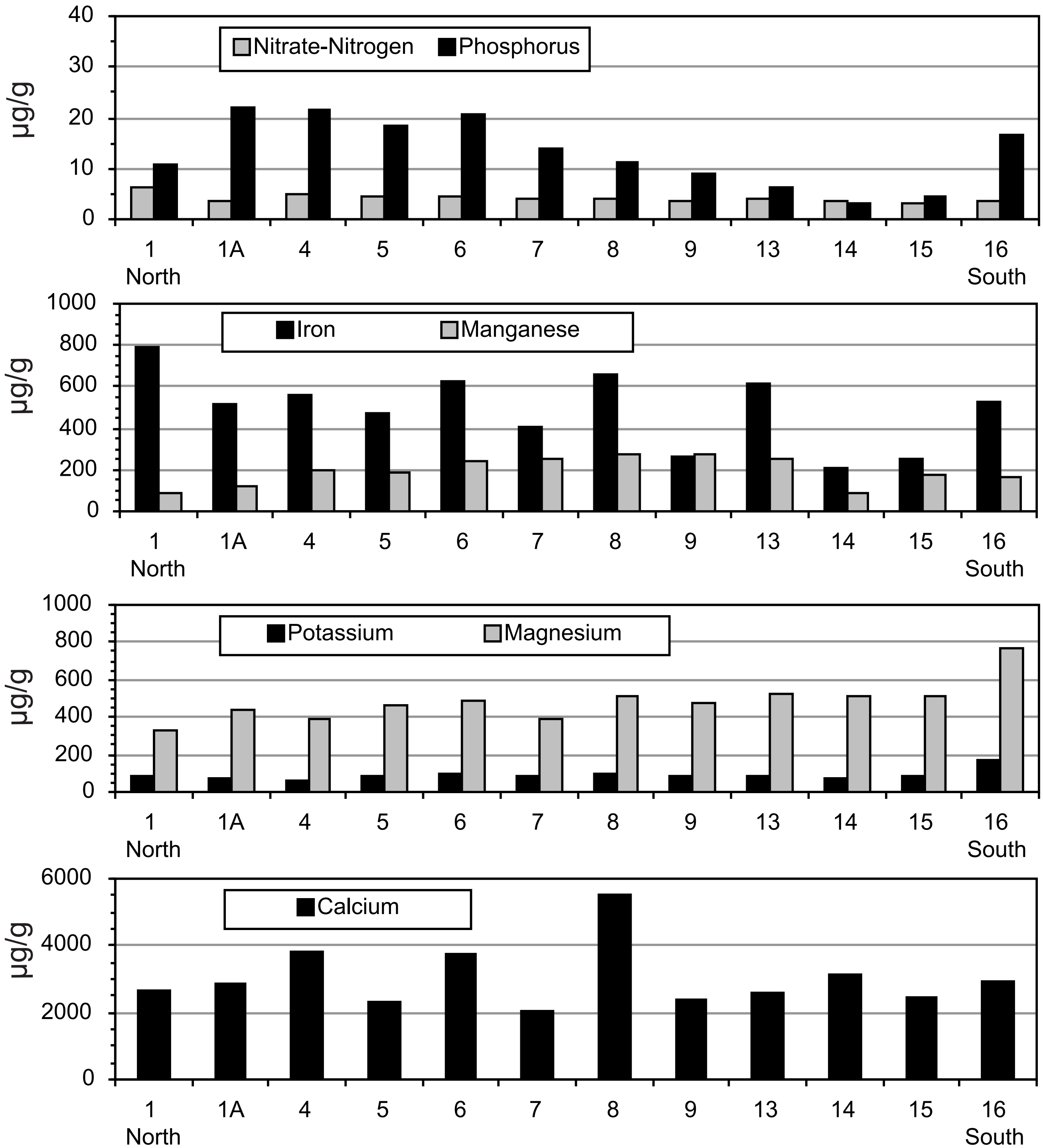

Figure 4. Billabong soil concentrations (μg/g) of nitrate-nitrogen and phosphate; iron and manganese; potassium and magnesium; and calcium - sample locations from north to south - October 2005.

to N_2O and N_2 (Mitsch and Gosselink, 2000). Filippi et al. (1998) hypothesize that the relatively high denitrification potential in the Billabong (i.e. higher than ORWRP Wetlands 1 and 2) is related to location of ground water influence and that groundwater intercepted by the Billabong is probably more reduced than the interstitial water in Wetlands 1 and 2, which is recent river water. This may explain the low concentrations of nitrate in the Billabong soils.

Phosphorus - Phosphorus (P) concentrations in the Billabong soils ranged from 3.2 to 21.9 μg-P/g, and averaged 13.2 μgP/g. This is one of only two parameters that had the hypothesized spatial distribution where higher concentrations (18.6-21.9 μg-P/g) were found at emergent *Typha* sites at the north end of the Billabong (Site Nos. 1A, 4, 5 and 6) and lower concentrations (3.2-6.4 μg-P/g) were found in the deep open water zone in the south end of the Billabong (Site Nos. 13, 14 and 15). The concentration then increases (to 16 μg-P/g) in the emergent vegetation zone near the outflow (Site No. 16). (Figure 4). Prior to construction of the ORWRP, soil phosphorus ranged from 7 to 69 μg-P/g and averaged 16 μg-P/g (Mitsch, 1993). This suggests that phosphorus concentrations were lower in 2005, but a sample site by sample site comparison would have to be done to know for sure.

Phosphorus is an essential component of plant nutrition and is a major constituent in fertilizers (Brady and Weil, 1999). Researchers have pointed out the importance of chemical composition of parent soils in wetlands for the retention of phosphorus (Mitsch, 1995), but how this influences concentrations in the Billabong would require further study. Brady and Weil (1999) indicate that under prolonged anaerobic conditions, iron is reduced making the iron-phosphate complex more soluble and causing release of phosphate into solution. This would also explain the low phosphorus concentrations in soils of the open water zone of the Billabong. Moreover, Pierzynski et al. (1994) note that transport of soil phosphorus occurs primarily via surface flow. Wang and Mitsch (2000), found that the major pathway of phosphorus retention through wetlands is through physical sedimentation rather than bio-assimilation.

Potassium - Potassium (K) concentrations in the Billabong soils ranged from 64 to 172 μg-K/g and averaged 92 μg-K/g. It is Site No. 16 (emergent *Typha* zone near the outflow) where the significantly higher concentration of 172 μg-K/g is detected. All the other sites are at or below 104 μg-K/g. (Figure 4). These results are comparable to the average concentration of 95 μg-K/g detected at the ORWRP in 1992, before construction of the experimental wetlands (Mitsch, 1993) and comparable to the concentrations of 84-162 μg-K/g detected at the experimental wetlands in 1994 (Wang et al., 1995).

Potassium is often deficient in soils and so it is the third main fertilizer element (Troeh and Thompson, 2005; Brady and Weil, 1999). As a result, agricultural runoff and river sediments are typically high in potassium (Brady and Weil, 1999). Plants take up about the same amount of potassium as nitrogen and about five to ten times more potassium than phosphorus (Brady and Weil, 1999).

Calcium - Calcium (Ca) concentrations in the Billabong soils ranged from 2048 to 5054 μg-Ca/g and averaged 3042 μg-Ca/g. (Figure 4). There was no particular spatial pattern in the results which are generally comparable to the average concentration of 2094 μg-Ca/g (range of 1685-3030 μg-Ca/g) detected at the ORWRP in 1992, before construction of the experimental wetlands (Mitsch, 1993) and comparable to the concentrations of 2150-3515 μg-Ca/g detected at the experimental wetlands in 1994 (Wang et al., 1995). However, the exceptionally high concentration of 5054 μg-Ca/g was found at Site No. 8, an open water area at the south end of the north half of the Billabong, rather than at the intake as expected. This suggests that there may be a sediment sink where the Billabong begins to widen and surface flow would hence slow down during hydrologic pulse events.

Calcium is a macronutrient essential for plant growth, but is seldom deficient (Troeh and Thompson, 2005). The source of the high calcium concentrations in the Billabong soil is calcite (CaCO3) and dolomite (CaMgCO3), which are common constituents of the parent soils and would also be imported in sediments from the Olentangy River as appeared to be the case in the ORWRC experimental wetlands 1 and 2 (Liptak and Mitsch, 1999). Liptak and Mitsch (1999) also indicate that calcite precipitation may play a role in immobilization of Phosphate and metals, however, Site No. 8 (5054 μg-Ca/g) had only a moderate phosphorus concentration (11.3 μg-P/g).

Magnesium - Magnesium (Mg) concentrations in the Billabong soils ranged from 326 to 774 μg-Mg/g and averaged 483 μg-Mg/g. In general the concentrations appear to rise gently from north to south with a jump at the very south end from 510 μg-Mg/g at Site No. 15 (deepest water site) to 774 μg-Mg/g at Site No. 16 (*Typha* zone near outflow). (Figure 4). These results are comparable to the ORWRP 1992 preconstruction soil concentrations which averaged 383 μg-Mg/g (Mitsch, 1993) and are also comparable to the 1994 ORWRP experimental wetland soil concentrations of 340-540 μg-Mg/g (Wang et al., 1995).

Sulfur - There was no discernable pattern of sulfur (S) concentrations in the Billabong soils, which ranged from 77 μg-S/g (at Site No. 15 – open water area at the south end of the Billabong) to 261 μg-S/g (at Site No. 8 – open water area at the south end of the northern half of the Billabong), and averaged 143 μg-S/g. (Figure 5).

Sulfur plays an important role in plant nutrition, but is also responsible for air, water and soil pollution, although that is not evident in the Billabong. Sulfur is held mainly in the soil organic matter, is subject to microbial oxidation and reduction, can enter and leave the soil in gaseous forms and is subject to some degree of leaching in the anionic form (Brady and Weil, 1999). Sulfate reduction occurs in anaerobic environments, but this is less of an issue in riparian type wetlands (Mitsch and Gosselink, 2000; Pierzynski et al., 1994).

Copper - Concentrations of copper (Cu) in the Billabong soils fluctuated up and down throughout the Billabong,

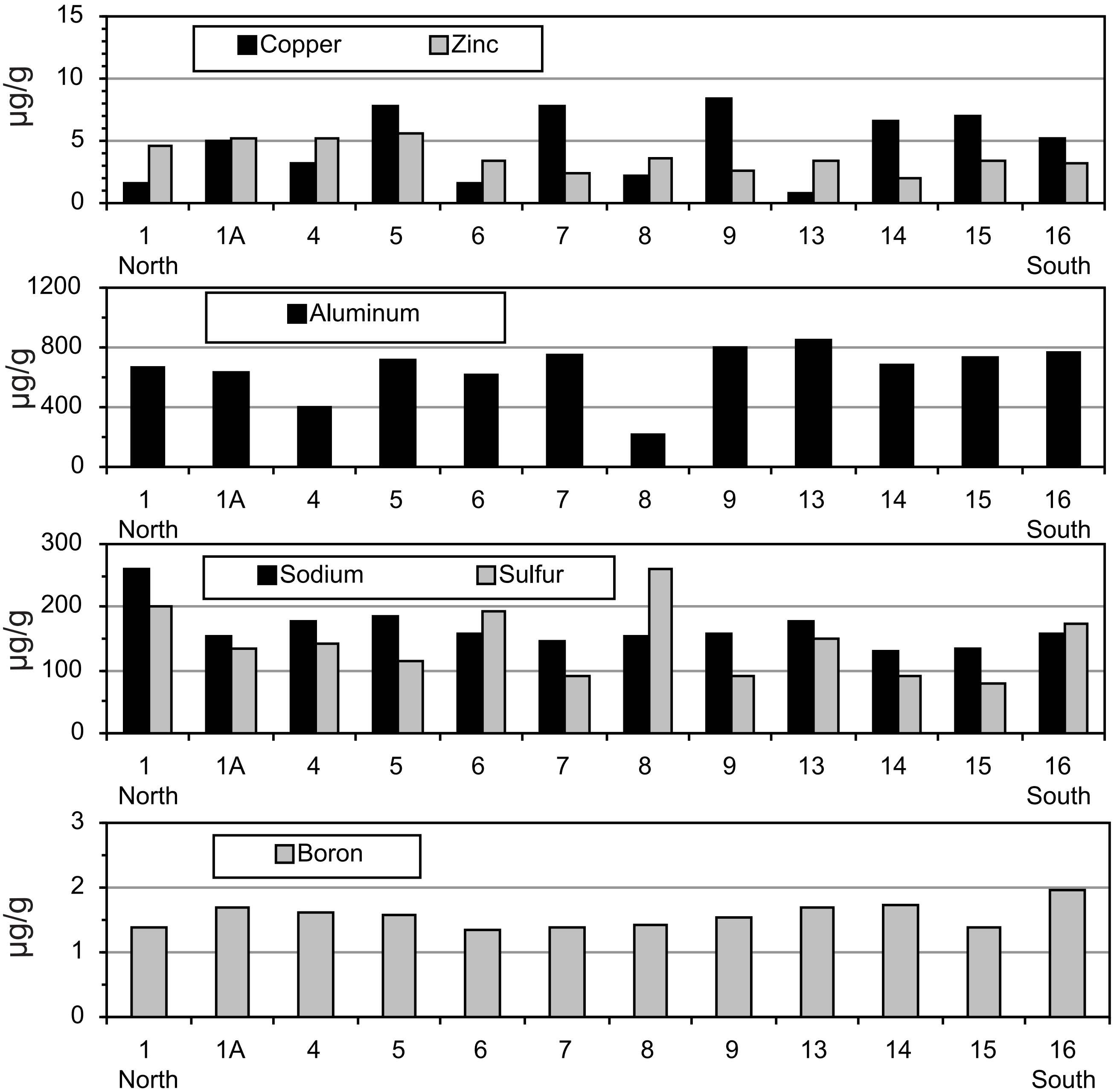

Figure 5. Billabong soil concentrations (μg/g) of copper and zinc; aluminum; sodium and sulfur; and boron - sample locations from north to south - October 2005.

ranging from 0.8 to 8.4 μg-Cu/g and averaging 4.8 μg-Cu/g. (Figure 5).

Zinc - Zinc (Z) concentration in the Billabong soils ranged from a low of 2 μg-Z/g to a high of 5 μg-Z/g, with an average over the Billabong of 3.7 μg-Z/g. The far north sites (Nos. 1, 1A, 4 and 5) averaged 5 μg-Z/g and the eight remaining sites averaged 3 μg-Z/g, a spatial distribution that was expected. (Figure 5).

Boron - Boron (B) concentrations in the Billabong soils ranged from 1.4 μg-B/g (at Site Nos. 7 and 8) to 2.0 μg-B/g at (Site No. 16 -*Typha* zone near outlet), and averaged 1.6 μg-B/g. (Figure 5). Boron is an important parameter because it can potentially cause phytotoxicity (Ahn and Mitsch, 1999), but this is most likely to occur under more arid conditions (Troeh and Thompson, 2005).

Iron - Iron (Fe) concentrations in the Billabong soils ranged from a low of 212 μg-Fe/g (at Site No. 9 – an emergent *Typha* zone) to a high of 794 μg-Fe/g (at Site No. 1 – north inflow), and averaged 492 μg-Fe/g. (Figure 4).

Iron is required in larger amounts than other micronutrients and iron deficiencies can occur even when large amounts of iron are present because some forms are very insoluble (Troeh and Thompson, 2005). Iron availability is less in alkaline soils (Brady and Weil, 1999).

Manganese - Manganese (Mn) concentrations in the

Billabong soils ranged from 87 μg-Mn/g (at Site No. 14 – an open water zone in the southwest) to 275 μg-Mn/g (at Site No. 8 – open water zone in the south part of the north half), and averaged 193 μg-Mn/g. (Figure 4).

Molybdenum - Laboratory results for molybdenum (Mo) concentration in the Billabong soils ranged from -0.037 to 0.047 μg-Mo/g, indicating laboratory error is nearly greater than the highest concentration detected.

Sodium - Sodium (Na) concentrations in the Billabong soils were highest (260 μg-Na/g) at the inflow (Site No. 1) and ranged from 131 to 186 μg-Na/g at the remainder of the sites tested. (Figure 5). Sodium is considered a non-essential element for plants, but may be beneficial in small amounts and can partially substitute for potassium in meeting plant needs (Troeh and Thompson, 2005).

Aluminum - Aluminum (Al) concentrations in the Billabong soils ranged from 224 to 845 μg-Al/g and averaged 655 μg-Al/g. The comparatively low value of 224 μg-Al/g was found at Site No. 8 (deep open water area at the south end of the north half). (Figure 5).

Aluminum is not considered essential for plant growth, but it is very abundant in soil minerals (Troeh and Thompson, 2005), which explains why it is relatively high across most of the Billabong. Considerable amounts of aluminum are absorbed by plants under acid conditions when it becomes toxic (Troeh and Thompson, 2005), but this is not the case in the Billabong.

Conclusions

Seventeen sites at the Billabong were tested for soil color, bulk density and percent organic matter. Of these, the twelve sites in the emergent *Typha* and open water zones were tested for soil pH and soil nutrients. Spatial distribution of these parameters was evaluated.

1. Results of the soil color analysis along with presence of mottles in some locations indicate that hydric soils have developed over a large portion of the emergent *Typha* and open water zones of the Billabong. The exception is one deep open water area in the southcentral portion of the Billabong and one of the emergent *Typha* zone sites. In contrast, hydric soils have not developed in the transitional/edge zones, although hydric soils were observed in one of the three upland areas at the north end of the Billabong.
2. Values of bulk density, percent organic matter and soil pH were consistent with previous investigations. They exhibited no particular pattern other than that pH was neutral at the inflow and alkaline at the ouflow. All are indicative of mineral soils.
3. Nitrate-nitrogen soil concentrations across the site are very low, which is indicative of denitrification. The highest concentration of nitrate was observed at the inflow indicating that denitrification is slightly greater throughout the rest of the site.
4. Concentrations of calcium, magnesium, phosphate and potassium in the Billabong soils were found to be generally comparable to concentrations detected in the ORWRP prior to construction, but within the expected range some spatial patterns were detected.
5. At the Billabong inflow, the highest concentrations of soil iron and sodium are detected. Near the ouflow, in a dense emergent *Typha* zone, the highest concentrations of soil potassium, magnesium and boron, along with a relatively high concentration of phosphorus, are detected.
6. Spatial distribution of phosphorus in Billabong soils was consistent with the expectation that higher concentrations would be found in sediments captured by the dense emergent *Typha* zone at the north end of the Billabong and that lower concentrations would be found in the deep open water zone in the south end of the Billabong. No other parameters except zinc exhibited this spatial distribution.
7. Where the Billabong begins to widen and surface water flow presumably slows, is likely another sediment sink, as suggested by the high concentrations of soil calcium, iron, manganese, sulfur and magnesium. However, concentrations of aluminum are lowest at that location.

Recommendations

Further investigation of the Billabong should evaluate location of sediment sinks. Comparison between soil and water samples taken at the same time and same locations within the Billabong should be performed. Future studies should also include a greater number of soil nutrient samples so that more detailed evaluation of patterns in spatial distribution of soil nutrients may be performed. A permanent grid system with permanent field markers should be established at the Billabong to reduce potential confusion as the total number of sampled sites increases over the years.

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